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THE BIOLOGICAL FLIGHT RESEARCH FACILITY

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SUMMARY

NASA Ames Research Center (ARC) is building a research facility, the Biological Flight Research Facility (BFRF), to meet the needs of life scientists to study the long-term effects of variable gravity on living systems. The facility will be housed on Space Station Freedom and is anticipated to operate for the lifetime of the station, approximately thirty years. It will allow plant and animal biologists to study the role of gravity, or its absence, at varying gravity intensities for varying periods of time and with various organisms. The principal difference between current Spacelab missions and those on Space Station Freedom, other than length of mission, will be the capability to perform on-orbit science procedures and the capability to simulate Earth gravity. Initially the facility will house plants and rodents in habitats which can be maintained at microgravity or can be placed on a 2.5 meter diameter centrifuge. However, the facility is also being designed to accommodate future habitats for small primates, avian and aquatic specimens. The centrifuge will provide 1 g for controls and will also be able to provide gravity from 0.01 to 2.0 g for threshold gravity studies as well as hypergravity studies. Included in the facility are a service unit for providing clean chambers for the specimens and a glovebox for manipulating the plant and animal specimens and for performing experimental protocols. The BFRF will provide the means to conduct basic experiments to gain an understanding of the effects of microgravity on the structure and function of plants and animals, as well as investigate the role of gravity as a potential countermeasure for the physiological changes observed in microgravity.

INTRODUCTION

The microgravity environment represents an important research tool for the life sciences. Its strategic use offers unprecedented opportunities to enhance our understanding of basic biological processes. Space Biology seeks to understand how living organisms, which have evolved in Earth's gravitational field, adapt both acutely and chronically to a microgravity environment. An extension of this type of research includes the development of countermeasures to maintain physiological responses at an appropriate level. Gravitational Biology seeks to understand the role that gravity plays in all biological processes as it affects form and function. Both Space Biology and Gravitational Biology require a laboratory in the microgravity environment with a centrifuge.

An inflight centrifuge which can provide controlled acceleration (artificial gravity) between 0 and 1-g is necessary if NASA is to take full advantage of the unique research resources of spaceflight. The capability to provide varying g-levels between 0 and 1 is not possible on Earth and an inflight centrifuge fills this critical gap in the fields of Space Biology and Gravitational Biology.

Moreover, the capability of the inflight centrifuge to produce artificial gravity to levels of 2.0 g will enable hypergravity studies. The major reasons for including an inflight centrifuge in the BFRF are to provide: (1) a 1-g control; (2) a means of examining gravity threshold effects; (3) a supply of gravity-conditioned specimens; and (4) development of intermittent hypergravity countermeasures. The rationale for these capabilities are:

1-g Control

A major use of the inflight centrifuge is to satisfy the need for a 1-g control environment in order to separate the effects of microgravity from those of other environmental factors. Rigorous research standards dictate the use of adequate controls to ensure that the variable of interest is the causal factor in any observed response. To date, ground-based controls have been used as the control for spaceflight biological experiments. However, spaceflight produces far more perturbations in the environment than simply an alteration in the g-field, e.g., varying radiation, atmospheric contaminants, vibration, illumination, magnetic field, and launch/reentry stress. Only through the use of an inflight 1-g control can the effect of microgravity be isolated from these other variables.

Gravity Threshold Effects

Life has always existed under a 1-g field. Therefore, a reasonable and important scientific question is how much can the normal gravity field be reduced or increased before significant changes are seen? Or, asked from a slightly different perspective, what is the minimum or maximal intensity and duration of gravity stimulus required to elicit a gravitational response? In order to determine gravitational effects satisfactorily, it is essential that the inflight centrifuge be capable of providing different gravity levels between 0-g and 1-g. Understanding threshold gravity levels is essential to the coherent development of gravitational biology as a more exact science.

Supply of 1-g Conditioned Specimens

The centrifuge can also be used as a specimen holding facility from which 1-g conditioned animals and plants can be obtained. The transition of biospecimens to microgravity can be made in a controlled manner permitting careful and repeated observations of the acute responses to a 1-g change in the ambient acceleration field. Similarly, biospecimens can be maintained under conditions of weightlessness and then transferred to the 1-g centrifuge to simulate the return to Earth's gravity. Readaptation to 1-g often occurs so quickly that Spacelab-flown animals cannot be retrieved soon enough to allow adequate study.

Intermittent Hypergravity Countermeasures

It is anticipated that within the next few decades space travel will involve long-duration manned missions to other planets. Both the United States and the Soviet Union have relied on physical exercise as a countermeasure for the crew to ameliorate the effects such as musculoskeletal loss and cardiovascular deconditioning caused by exposure to the microgravity environment. However, another approach may be the use of hypergravity at intermittent intervals to prevent microgravity deconditioning. The centrifuge will allow the initial systematic study of the effect of g intensity versus duration as a countermeasure in rodents.

HARDWARE

The major hardware items within the BFRF comprise a suite of hardware known collectively as the Centrifuge Facility and it is that suite of hardware which will be described in this paper. The Centrifuge Facility (CF), shown in figure 1, includes a micro-g habitat holding unit, a large diameter centrifuge, a glovebox, a specimen chamber service unit and the modular habitats which are housed either in the holding unit or the centrifuge. NASA Ames has just concluded a competitive Phase B design concept study with McDonnell Douglas Space Systems Division, Huntington Beach, CA and with Lockheed Missiles and Space Company, Inc., Sunnyvale,CA which demonstrated that it is possible to build the facility and remain within the power, volume and weight constraints of Space Station Freedom. Because these design concepts are proprietary, the discussion of the hardware will be restricted to functional and scientific uses of the hardware. The facility is an integrated suite of equipment which must function together. A key element is the modular habitat. The habitat is designed to fit either within the holding unit or on the centrifuge, and to mate with the glovebox. Hence, interfaces must be compatible between the holding unit, the centrifuge and the glovebox. Furthermore, the habitat may also be used to transport specimens to and from orbit.

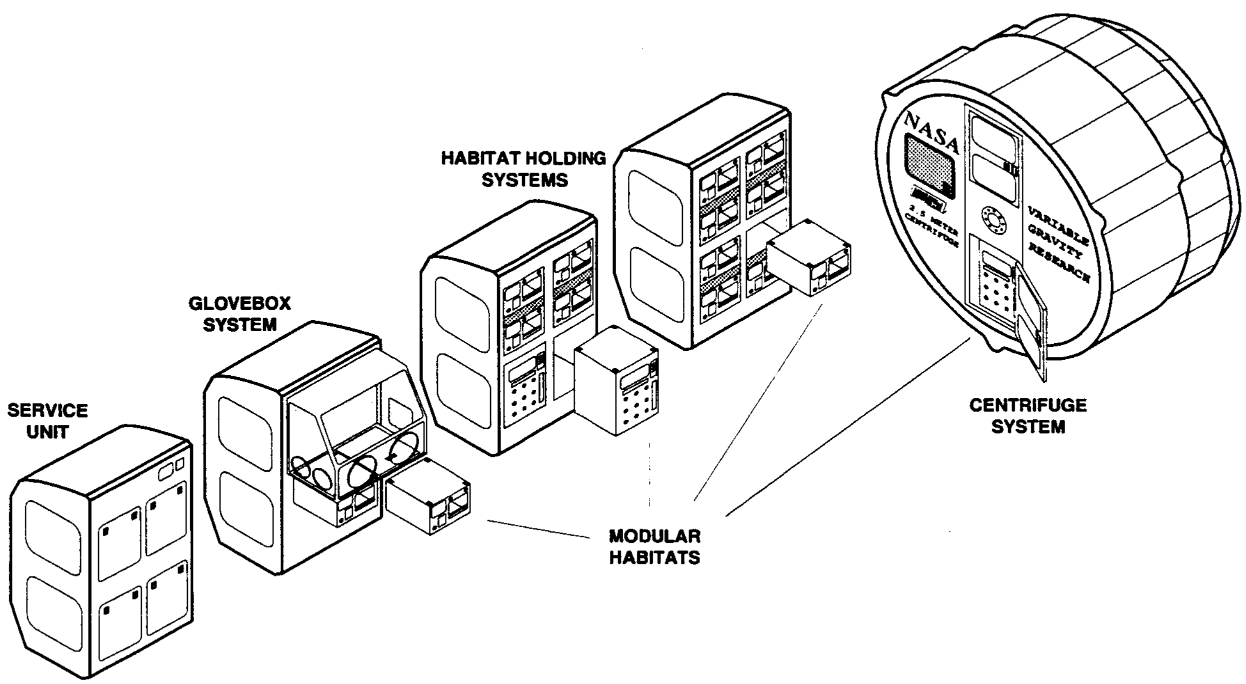

Figure 1. Centrifuge facility.

Centrifuge

A 2.5 meter diameter centrifuge has been baselined for Space Station Freedom. Initially, a 1.8 meter diameter centrifuge was proposed since that was the largest diameter centrifuge which could be mounted in a rack in the science laboratory module. However, when the decision was made to place the centrifuge in a node of SSF rather than in the science laboratory module, it was possible to enlarge the diameter to approximately 2.5 meters by mounting it in the end-cone of the node. The increased diameter of the centrifuge enhanced science capability as well as relieved engineering packaging constraints. The increased diameter of the centrifuge significantly reduced the gravity gradient across the specimens, increased the number of specimens which could be accommodated on the centrifuge and permitted the inclusion of an inner concentric row of habitats on the centrifuge rotor allowing two gravity levels to be run simultaneously. An ARC concept of the 2.5 meter diameter centrifuge mounted in a node is shown in figure 2.

The centrifuge will provide a 1-g control environment, and varying levels of g for threshold and other studies, and allow the development of countermeasures/artificial gravity techniques, including intermittent hypergravity exposures. The centrifuge will be capable of gravity levels from 0.01 to 2 g with a nominal spin-up rate which limits the acceleration experienced by the specimens to less than

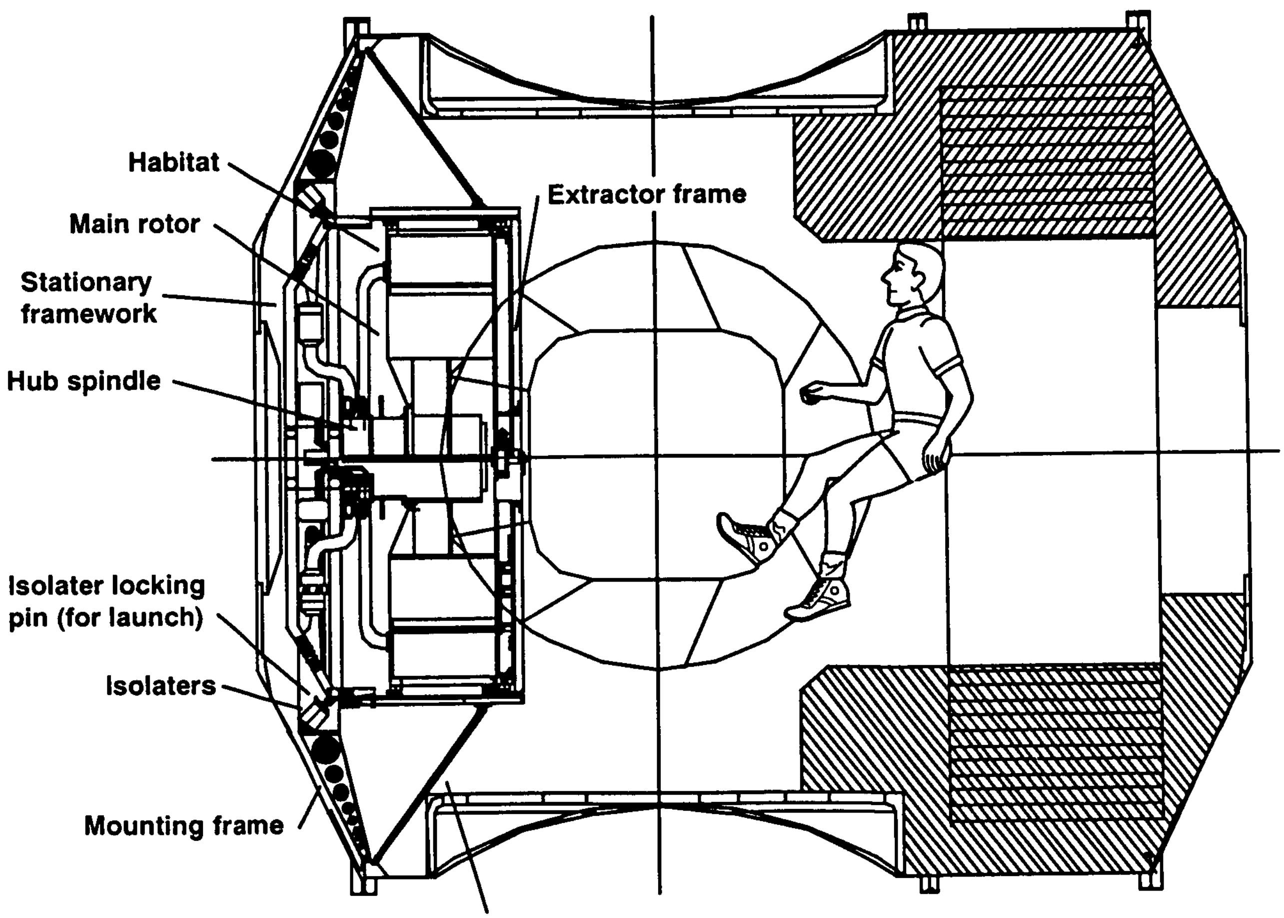

Figure 2. ARC concept of the 2.5 meter diameter centrifuge mounted in a node.

0.01 g per second. It will provide life support for both plants and animals. The control accuracy of the g level is 0.01 g at the higher g levels with less than 0.001 g vibration imparted to the specimens in the habitat in the range of 5 to 100 Hz. A momentum compensation mechanism will be incorporated into the design of the centrifuge to minimize attitude changes of Freedom during centrifuge starts and stops and the very small torque (2-5 ft-lb) due to gyroscopic effects. Several approaches have been studied, the simplest being no additional mechanism and use of the Control Moment Gyros (CMGs) of the station itself. Most cases studied show this to be a viable approach.

A unique feature strongly endorsed by the science community is a service rotor which can extract habitats from the centrifuge without having to stop the main rotor. This feature will minimize the disturbance to other habitats on the centrifuge during routine servicing of the habitats, including waste tray changeout and food replenishment. In addition to enhancing the science capability of the centrifuge, the service rotor also has some engineering benefits. It significantly reduces the mass which must be spun up and spun down for access to the specimens and hence reduces momentum compensation activity and the power required for that operation. Conversely, it increases the engineering complexity of the centrifuge by adding a subsystem which must have the capability to spin up and precisely match the speed of the main rotor, engage and extract or insert habitats and spin down.

During centrifuge operation there may be a dynamic mass balancing system to compensate for variations in mass distribution along the rotor over the life of an experiment. The balance system and vibration isolation system are expected to limit forces coming from the centrifuge to less than about 0.1 pound in the frequencies near the centrifuge spin rate. This value was derived from a preliminary analysis which attempted to determine the magnitude of a sole disturbance force that would create g-jitter in the US laboratory exceeding 10^{-6} g. The NASA Office of Space Science and Application requires this ultra quiet environment for the performance of material science's experiments. However, one must keep in mind that nominal crew movement and SSF operations may impart as much as 10^{-3} g.

Life support functions not directly incorporated into the habitat are placed on the centrifuge. In the ARC study these include air thermal conditioning and distribution, condensate collection, and specialized gas supply. The life support functions on the centrifuge are analogous to those in the habitat holding unit and are shown in figure 3.

Habitat Holding Unit

The habitat holding unit occupies a International high double rack and is capable of holding either rodent habitats, plant habitats or a combination of both. Since the habitats must be accommodated on the centrifuge, in the habitat holding unit, and the glovebox, the interface plate on each must be identical and the partitioning of services between the holding systems and the habitats must be the same.

A block diagram showing the ARC concept for life support of a habitat and the habitat holding unit is show in figure 3. The habitat holding unit and the centrifuge condition the inlet cabin air by HEPA and charcoal filtration and temperature and humidity regulation. Air enters the system

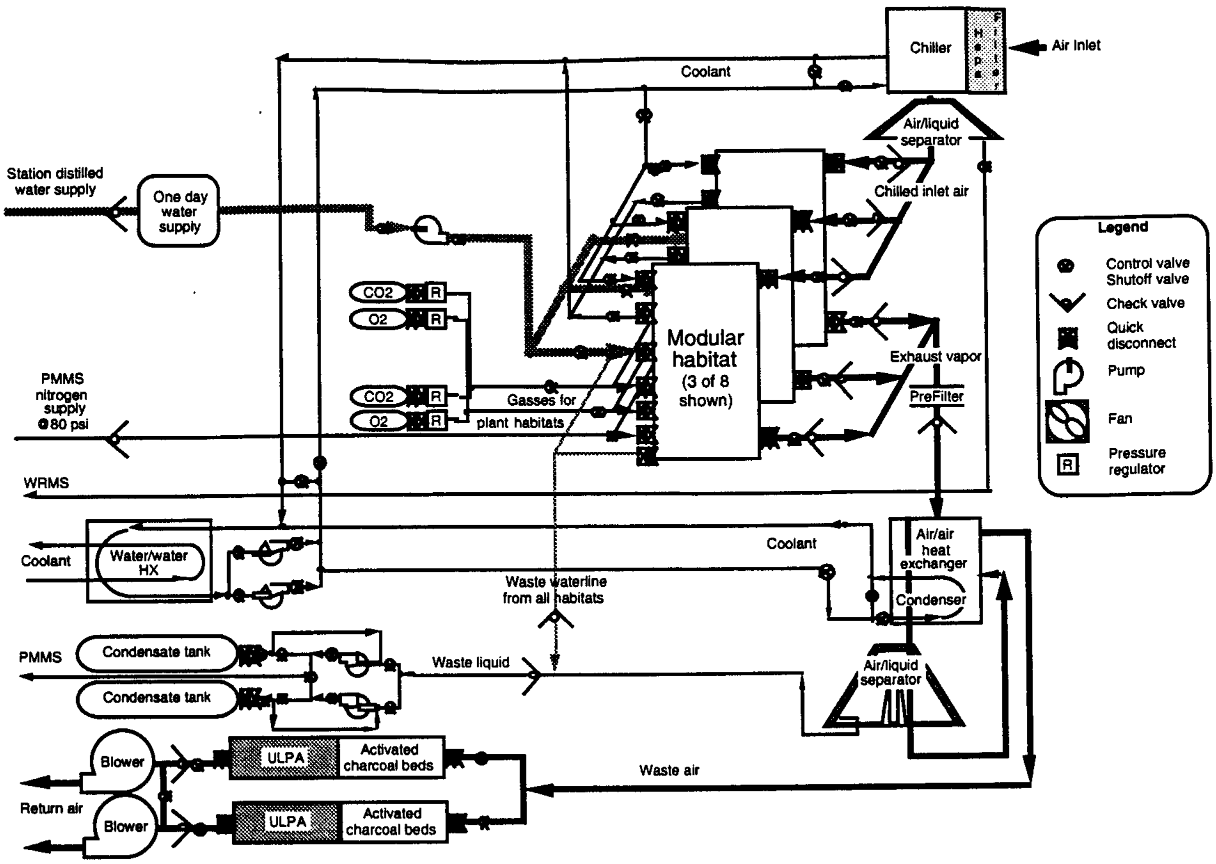

Figure 3. ARC life support block diagram for the habitat holding unit and habitats.

through a heat exchanger and an air-liquid separator which conditions it to the lowest temperature and humidity level required by the habitats. Heaters and humidifiers within the habitats adjust the temperature and humidity to the required values. Air exiting the habitats passes through an air-to-air heat exchanger and an air/liquid separator to reduce moisture content and finally through a charcoal bed and HEPA filter before returning to the cabin. This meets Freedom's particulate and ECLSS requirements of not contributing to the bioburden in the cabin or adding excess heat and humidity to the cabin atmosphere.

In addition to the life support systems mentioned above, both the holding unit and the centrifuge include a data management system and display panel for monitoring the environmental parameters of the habitats. The data management system accommodates hard-wired, telemetered data and video. The data signals are processed by the habitat holding unit subsystems to meet Freedom data network requirements prior to transferring the data to Freedom's Data Management System (DMS) which transmits the data to the ground either in real time, near real time or as time permits. The data system will have limited data storage capacity and may have data compression capability. A representative list of the types of rodent data which will be collected in the facility is shown in table 1. The system is being designed to anticipate future needs and not limit the type of data to be generated by investigators in the decades to come.

Table 1. Representative data requirements for rodents

Sensor	Sample Rate/Channel
EMG	4000
ECG	600
Tendon Force	200
Brain μelectrode	20,000
EEG	300
EOG	250
Cardiac Dimension	250
Blood Flow	300
Core Temperature	0.02

Modular Habitats

Two types of habitats are being designed for biospecimens, one for rodents and one for plants. A third habitat is under consideration for small primates but was not part of the scope of the recently completed Phase B contract. The two contractors considered the design implications of having to accommodate a larger primate habitat and designed the habitat holding unit and centrifuge in such a way as not to preclude a small primate habitat as a growth option.

Rodent habitat– The rodent habitat is to house both rats and mice either in a group or individually. The habitats differ significantly from the Research Animal Holding Facility (RAHF) currently flown on Spacelab. The major differences are level of containment (ref. 1), range of temperature, video capability both in the light and dark cycle, adjustable light level, on orbit refurbishment of cages, and hard-wired data collection system (ref. 2).

Although some of these features are mandated by the necessity to maintain biospecimens on orbit in a closed environment, others will provide greater scientific return and range of experiments than currently possible with the RAHF. Because Freedom is a long duration facility with planned increments of 90 days between resupply visits, the habitats must be designed to be cleaned on orbit efficiently and without releasing contaminants into the cabin environment. The animal habitats will provide two levels of containment. The habitat itself provides a physical barrier and is also maintained at a negative pressure (minimum 0.5" water gauge) with respect to the cabin atmosphere. Thus, if the physical integrity of the habitat should fail, the leak would be into the habitat rather than into the cabin environment. All servicing of the habitat will be performed at the glovebox. No servicing will be done at the rack front as is done on Spacelab. The habitats will be provided with an auxiliary fan for air circulation while the habitats are being transported from the habitat holding unit or the centrifuge to the glovebox. The habitats will mate with the glovebox in such a manner as to prevent particulates from escaping into the cabin. Two methods of cleaning the specimen chambers were investigated—washing of the soiled chambers and replacement with disposable chambers. The latter method was chosen because it did not require any power and because it was felt that the technology for recycling water from a cage washer was not sufficiently mature.

The temperature within the rodent habitats will be controllable over the range of 18-27° C ±1° C in increments of 1° C. Precise control of this parameter will extend the range of experiments to be performed on orbit to include study of the thermoregulatory system and the use of compromised rodents, e.g., hypothymectomized rats. The inclusion of a video system to monitor animals during both the light and dark cycle will permit behavioral studies as well as provide needed activity data to further elucidate observed changes in the musculoskeletal and cardiovascular systems attributed to the microgravity environment. The habitats will also provide control of the illuminance and the photoperiod. The illuminance will be controllable over the range of 5-100 lux in increments of 5 lux and the photoperiod will be controllable to within ± 1 minute with independent adjustable light and dark periods without being constrained to a 24 hour cycle. This will permit controlled experiments to determine the effect of the microgravity environment on response to light levels, on circadian rhythms and on the thermoregulatory system.

Plant habitat– The science requirements for the plant habitat are ambitious and may be difficult to achieve, especially during the early phases of Space Station Freedom . If achievable, they will provide a unique facility in which to conduct basic plant physiology and far surpass the environmental control achievable with the Plant Growth Unit (PGU) currently used in the Shuttle middeck (ref. 3). Some of the science requirements are: temperature control in the range of 15-30° C ±1° C; independent atmospheric control of O_2 (5-27% ± 0.5%) and CO_2 (300-5000 ppm ± 1%), ethylene <5 ppb, air velocity 0-10 changes/hour ±5%, photon flux 0-600 µmole/m^2/s ±5%, solid or liquid growth matrix, and field or subdividable growing area. Engineering studies by the Phase B contractors suggest that it is not possible to meet all of the science requirements simultaneously and that it will be necessary to restrict the range in which they can be met. For example, at high flux levels it is not possible to meet the current temperature uniformity requirement at low air velocity. Hence one must either relax the temperature requirement or relax the requirement to provide low air flow at high flux. Nevertheless, even if the above requirements cannot be fully met, the flux level and control of atmospheric conditions in the plant habitat will be a significant improvement over the PGU (75 µmoles/m^2/s and open loop to cabin environment). The plant habitat provided for the BFRF will provide sufficient control of the necessary parameters to advance Space Biology and Gravitational Biology, particularly in the areas of photosynthesis, metabolism and nutrient transport. It will also provide much needed information on how to design the next generation plant habitat for use in the microgravity environment.

Other habitats– Although the CF is only providing rodent and plant habitats, the habitat holding unit and centrifuge are being designed with sufficient capability and flexibility to accommodate advanced habitats, i.e., metabolic, avian, aquatic, provided that these habitats can meet the interface requirements These include compatible air, water, thermal control, data, and power connectors. Accurate temperature and atmospheric control and monitoring capability within the advanced habitats would be within the habitats themselves, as they are in the rodent and plant habitats.

Specimen Chamber Service Unit

Initially, the specimen chamber service unit (SCSU) was envisioned as a cage washer capable of washing and sterilizing specimen chambers for reuse and of recycling the water required for that process. However, an ARC study concluded that it would be more feasible and resource-effective to provide disposable specimen cages than to wash the cages on orbit and to recycle the dirty water (ref. 4). The SCSU is essentially a storage unit which will supply clean specimen chambers, waste management trays, and food for the rodent habitats as well as storing the spent units. Because dirty specimen chambers and waste trays will also be stored in the SCSU, it will be necessary to incorporate into the design of the SCSU a waste management subsystem to limit and control the release of biologically produced gasses. The waste management subsystem will have to meet Freedom's requirements for particulate, microbial, and odor control.

Glovebox

The glovebox, in which all servicing and experiment protocols will be performed, is classified as a modified Class III Biological Cabinet because it does not have a dunk box or an airlock and vents to an interior space. Instead, the habitats and equipment transfer boxes will mate in a fully sealed manner with the glovebox to meet Freedom particulate containment requirements. Moreover, because Freedom is a closed environment, sufficient contamination control will be included in the glovebox air exchange system to prevent the release of chemicals which could exceed the Spacecraft Maximum Allowable Concentration (SMAC) levels. The current Space Station volume allocation limits the glovebox to an International standard double rack but that volume may constrain the performance of life sciences experiment tasks. In order to accommodate two workers simultaneously, a glovebox which can be deployed into the aisle is proposed. The ARC concept is shown in figure 4.

Data and electrical ports to support experiment unique equipment and general laboratory support equipment will be provided in the work volume. Also included will be a video system for recording/ transmitting operations within the glovebox. In addition to performing the functions normally associated with a Class III Biological Cabinet, the glovebox will provide some life support to the habitats while they are connected to it for servicing and performance of experiment protocols. The glovebox will have an interface plate identical to that in the habitat holding unit and centrifuge which will provide power and air to maintain the specimens at nominal conditions. While connected to the glovebox, the specimens will be maintained at approximately cabin temperature and humidity.

CONCLUSION

The pieces of hardware described above are the major elements of the Centrifuge Facility. The centrifuge occupies the equivalent of two standard double racks but will be mounted in the end cone of a node or in a specialized module to take advantage of the full diameter of the Space Station structure. The habitat holding unit, specimen chamber service unit and glovebox each occupy a standard double rack bringing the volume of the Centrifuge Facility to approximately five double racks or six double racks if two habitat holding units are included. The power requirements of each of the standard double rack elements is within the 3 kW supplied to each rack by Station.

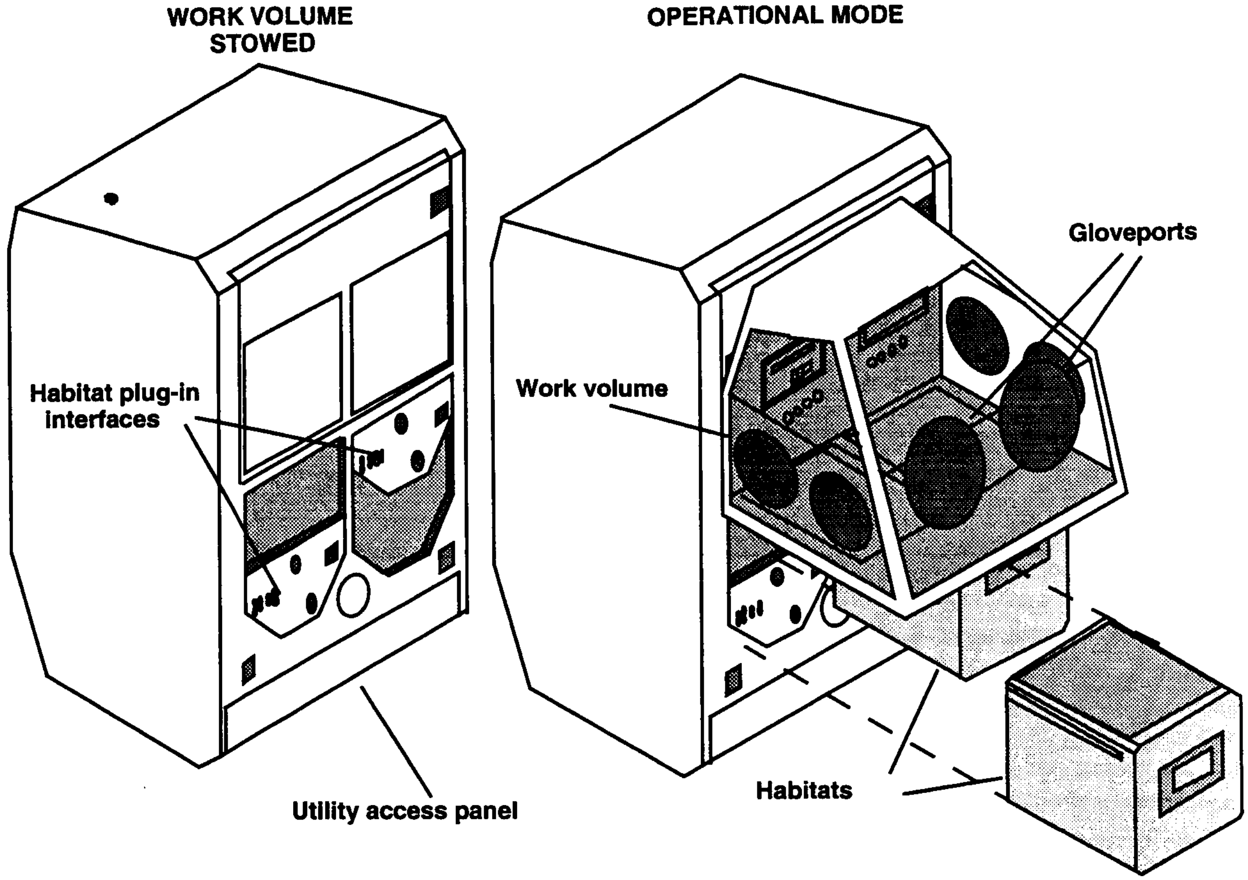

Figure 4. ARC concept for a deployable glovebox.

The Centrifuge Facility represents a major commitment to the performance of Life Sciences research on Space Station Freedom by the NASA Office of Space Science and Applications. It will continue the investigations begun on Spacelab and greatly expand the capability to perform onboard analyses. The Facility will permit the life sciences community to fully exploit the microgravity environment and use gravity as a research tool to understand basic biological processes and the response of both plants and animals to the lack of gravity. Information learned from understanding the mechanism by which plants and animals adapt will provide the foundation for designing effective countermeasures for man's eventual exploration and habitation of the moon and Mars.

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BIOGRAPHY

Catherine C. Johnson received a Bachelor of Arts in Biology from Stanford University in 1963 and has been employed at NASA Ames Research Center since 1964. She analyzed lunar samples from the Apollo 11 Mission both in the lunar quarantine facility at Johnson Space Center and at Ames Research Center for evidence of biologically significant compounds and microbial life. She also worked on the development of the gas exchange experiment which flew on the Viking lander to Mars and on the Solar Sail for a proposed rendezvous with Halley's Comet. She joined the Biological Flight Research Projects Office (BFRPO) in 1985 where she is the science task manager. The BFRPO is responsible for developing hardware to support non-human life sciences research on Space Station Freedom. Prior to joining the BFRPO she worked in the area of Advanced Life Support specializing in water reclamation and solid waste management using reverse osmosis, wet oxidation and supercritical water oxidation technology. She is a member of the American Institute of Aeronautics and Astronautics and of the American Society of Gravitational and Space Biology. She has published over 40 papers, holds a patent, edited two NASA Technical Memorandum, and served on several technical committees. She is the recipient of two NASA Achievement Awards and three NASA Certificates of Recognition. She is married to Richard D. Johnson and has two sons, Eric 20 and Greg 12.